(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 667 683 A2

(12) EUROPEAN PATENT APPLICATION

(21) Application number: 95100287.2

(22) Date of filing: 11.01.95

(51) Int. Cl.6: H04B 1/10, H04B 7/26

(30) Priority: 10.02.94 GB 9402564

(43) Date of publication of application:
16.08.95 Bulletin 95/33

(84) Designated Contracting States:
DE FR IT SE

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(54) Multi-user interference cancellation for cellular mobile radio systems.

(57) A communication system wherein known data sequences characterise both wanted transmitted signals and interfering co-channel transmitted signals, comprising a receiver for receiving a wanted transmitted signal in the presence of unwanted co-channel interfering signals comprises signal sequence identifier means which includes a store for known data sequences and a correlator which serves to correlate received signals with the stored known data sequences, whereby the relative location in time of received signal sequences is identified, impulse response estimator means operative for estimating the impulse response of each signal the location of which has been identified, means responsive to the estimated impulse responses for producing in respect of each said response a set of possible signal configurations, and detector means including means for comparing the signals of each set with the received signal thereby to filter the wanted signal.

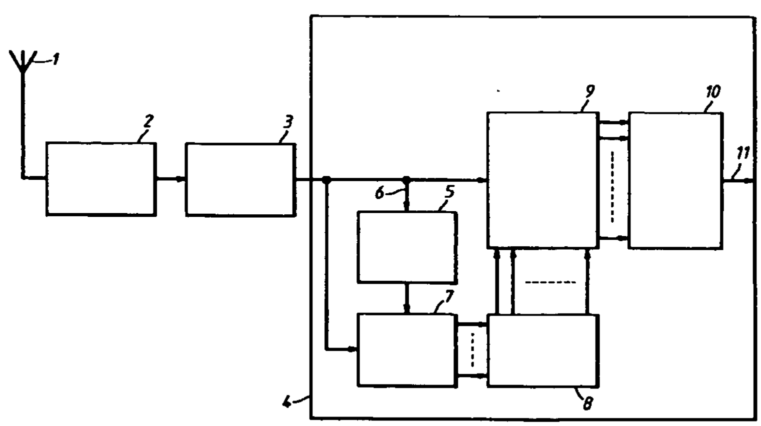

Fig.1

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This invention relates to co-channel interference suppression systems and more especially, although not exclusively, it relates to co-channel interference suppression systems for use in land based cellular mobile radio systems.

In many radio systems, available frequencies are re-used geographically to provide a high traffic capacity with minimal spectral utilisation. Frequency use however, is fundamentally limited by the tolerance of a receiver to co-channel interference. Although transmission formats largely dictate the extent of this tolerance, techniques such as antenna diversity reception, adaptive power control or adaptive antennas may be used to improve upon this.

Adaptive and diversity antennas have limited application however, and ideally the provision of a means for the suppression of co-channel interference using the signal from a single antenna would be desirable.

The level of interference that a receiver can tolerate, fundamentally limits system capacity, because frequencies (or channels) are reused spatially. The more interference a receiver can tolerate, the greater the proportion of available frequencies can be used at each base station. Receivers in land based mobile radio systems are rarely designed to account for the presence of interference, rather the system is configured to reduce the level of interference experienced to an acceptable level. If however, the detection processes in a receiver are modified explicitly to account for the presence of a number of like modulated co-channel interferers, then potentially the receiver can tolerate a much greater level of co-channel interference and the system capacity can therefore advantageously be increased.

It is an object of the present invention therefore to provide a system which will operate to suppress like digitally modulated co-channel interference using the signal from a single antenna.

It is a further object of the present invention to provide a system which lends itself to be applied to an existing system with minimal modification thereto.

According to the present invention in a communication system wherein known data sequences characterise both wanted transmitted signals and interfering co-channel transmitted signals, a receiver for receiving a wanted transmitted signal in the presence of unwanted co-channel interfering signals comprises signal sequence identifier means which includes a store for known data sequences and a correlator which serves to correlate received signals with the stored known data sequences, whereby the relative location in time of received signal sequences is identified, impulse response estimator means operative for estimating the impulse response of each signal the location of which has been identified, means responsive to the estimated impulse responses for producing in respect of each said response a set of possible signal configurations, and detector means including means for comparing the signals of each set with the received signal thereby to process the wanted signal.

The sequence identifier means may be fed with the received signal via a baseband signal converter and an A to D converter which in combination serve to provide digital signal samples of the received signal at baseband frequencies.

The said means for comparing the signals of each set with the received signal may comprise a metrics generator responsive to the said sets for providing signals for a sequence estimator comprising a trellis processor from which processor an output signal comprising a detected data sequence corresponding to the wanted signal is provided.

The baseband signal converter may be fed with a signal from a single antenna and apparatus according to the present invention may be used instead of a demodulator/equaliser in an existing system thereby to provide improved co-channel interference suppression with minimal modification to the existing system.

One embodiment of the invention will now be described by way of example only with reference to the accompanying drawings, wherein:

FIGURE 1 is a simplified block schematic diagram of a land based mobile radio receiver,

FIGURE 2 is a block schematic diagram of the metrics generator 9 shown in Figure 1,

FIGURE 3 is a block schematic diagram of the signal set generator 8 shown in Figure 1,

FIGURE 4 is a diagram illustrating operation of the sequence estimator 10 shown in Figure 1, and

FIGURE 5 is a diagram illustrating operation of a super-state trellis.

Referring now to Figure 1 of the drawings, the receiver comprises a single aerial 1 which is arranged to feed an RF to baseband signal converter 2. Output signals at baseband from the RF to baseband signal converter 2 are fed to an analog to digital converter 3 which provides digital signal samples of the received baseband signal. These samples are fed to an interference suppression unit 4 comprising operational blocks which will now be described and which are shown within a shaded region of the drawing. The interference suppression unit comprises a known sequence locator 5 including a store which is primed with all known data sequences and a correlator which serves to correlate a received signal, present on a line 6 which is fed from the A to D converter 3, with the known data sequences contained within the store.

Position estimate signals from the known sequence locator 5 appertaining to the received signal are fed to an impulse response estimator 7 which serves to calculate in respect of each data sequence signal identified, a corresponding impulse response, the character of which is determined by the channel path in the ether through which the signal has travelled. As will readily be appreciated, the wanted signal and the unwanted signals will each be characterised by a different impulse response since they travel through different channel paths. Signals from the impulse response estimator 7 are fed to a signal set generator 8 which serves to produce a set of possible signals in respect of each signal. The signal sets thus produced are fed to a detector arrangement comprising a metrics generator 9 and a sequence estimator 10 (which is in effect a trellis processor), thereby to provide an output signal on a line 11, which comprises an estimated data sequence corresponding to the wanted received signal. The metrics generator and the sequence estimator or trellis processor 10 in combination serve in effect to compare the signals of each set with the received signal, whereby the wanted signal is detected.

The manner in which the individual blocks of the interference suppresser 4 operate will now be described in greater detail with reference to Figures 2, 3 and 4.

Referring now to Figure 2, which shows in more detail the metrics generator 9, received signals from the A to D converter 3 are fed on a line 12 to a number of MAC units 13, 14, 15 and 16 which serve to multiply and accumulate over each data symbol period received signal samples on the line 12 with signals from the signal set generator 8 that are applied to lines 17 to 22. Although only four MAC units 13, 14, 15 and 16 are shown in Figure 2, it will be understood that one MAC unit will be provided for each possible signal in the signal set in Figure 1. Signals from the MAC units 13 and 14 are fed via switches 23 and 24 to an adder 25 and signals from the MAC units 15 and 16 are fed via switches 26 and 27 to an adder 28 thereby to provide output signals on lines 29 and 30 respectively for subtraction units 31 and 32 which are fed also via lines 21 and 22 respectively with signals from the signal set generator 8, thereby to provide output signals on lines 33 and 34 which are fed to the sequence estimator 10.

Referring now to Figure 3, the signal set generator 8 is fed on lines 35 and 36 from the impulse response estimator 7 with signals corresponding to the wanted impulse response and the interferer impulse response respectively. The lines 35 and 36 are arranged to feed multipliers 37, 38, 39 and 40, which multipliers are fed also from a store 41 containing all possible signal patterns over a predetermined number of symbol intervals. Output signals from the multipliers 37, 38, 39 and 40 are fed on lines 42, 43, 44 and 45 to a temporary store 46 which contains results of a convolution. Output signals are produced on lines 47, 48, 49 and 50, only four of which are shown in the drawing, thereby to provide input signals for the metric generator 9.

Referring now to Figure 4, the sequence estimator 10, which in effect comprises a trellis processor, operates on the signals provided from the metrics generator 9 as shown in Figure 1 and comprises the digital state possibilities as indicated in column 51 of Figure 4, so as to provide an output signal on the line 11 which corresponds to that signal which has the largest probability over between 10 to 20 data symbols.

More detailed operation of the apparatus hereinbefore described will now be considered. Considering firstly the sequence estimator 10, an efficient optimum technique for performing maximum likelihood sequence estimation is the Viterbi algorithm. The Viterbi algorithm is generally well known to those skilled in the art, but attention is hereby directed to IEEE Proc., Volume 61, 1973, pages 268 to 278 for further information. In applying the Viterbi algorithm to conventional equalisation/demodulation problems the output of the channel prior to noise addition is viewed as a finite state Markov process. For linear modulation methods the states of this process relate to data sequences of length v, which span the memory of the channel and modulation process. The output of the channel can then be described by a sequence of these states, and the task of the Viterbi algorithm is to find the sequence of states with the highest probability of occurrence. This sequence becomes the estimated data sequence, ie the output 11. If each state in the conventional equalisation/ demodulation process for the single signal is described by a state descriptor ξ_i for the i-th state. As each interfering signal can be similarly described, then for the K interfering signals, the super-state Ξ_i can be defined as being formed from the K+1 state descriptors of the K+1 signals: $\Xi_i = (\xi_{i0},...\xi_{iK})$. If there are S states describing each signal, then there are S^{K+1} super-states, and because each set of states describes a finite state Markov process, then this property applies to the super-states also. Describing each state by the v-tuple of data symbols: $(a_{n-1},...a_{n-v})$,
$a_i \in [0,M-1]$, then there are M transitions emanating from each state, corresponding to the M possible values that the n-th data symbol can take. So from each super-state there are M^{K+1} transitions. The progression of a data sequence in terms of its state description can be represented on a trellis diagram, which shows all possible transitions between super-states at time (n-1)T and time nT. The trellis diagram of the super-state trellis for $M=2;v=1;K=1$ is depicted in Figure 5.

This is the simplest non-trivial super-state trellis for this particular problem; applying to a binary modulation, a single interferer and where the channel and modulation process have a memory of one symbol. For each transition in the trellis the following incremental metric is calculated which is effected by the metric generator 9.

$$\gamma_{i,j} = \sum_{l=0}^{\lambda-1} \left| r(l+n\lambda) - \sum_{k=0}^{K} c_k(l, a_k^{i,j}) \right|^2 \qquad \text{.... (1)}$$

Where $\gamma_{i,j}$ is the incremental metric for the transition between super-state i and super-state j. The data symbol sequences of length v+1 symbols causing this transition are denoted by

$$a_k^{i,j}.$$

In equation (1), r(l) is the l-th sample of the received signal at time lT/λ, where λ is the number of samples per data symbol period (T). The signals

$$c_k(l, a_k^{i,j})$$

are generated by the signal set generator 8, from the impulse response of the k-th channel, according to equation (2) below:

$$c_k(l, a_k^{i,j}) = \sum_{j=0}^{D\lambda} h_k(j)\ S(l-j, a_k^{i,j}) \qquad \text{.... (2)}$$

Where D is the duration of the channel impulse response in symbol periods, $h_k(j)$ the j-th coefficient of the channel impulse response for the k-th interferer, obtained from the channel impulse response estimator 7. The accumulated metric for the i-th super-state is denoted by Γ_i, and so for the n-th data symbol the following selection procedure is performed at each superstate.

$$\Gamma_j = \min_{i \in \alpha} [\Gamma_i + \gamma_{i,j}] \qquad \text{.... (3)}$$

Where α is the set of super-states merging in the j-th super-state. At the j-th new state, the old state that gives rise to the smallest accumulated metric is added to a buffer, which stores the sequence of states leading to the j-th state. If the observation length of the receiver is N symbols, then the detected data symbol is recovered from the state stored N symbols previously, and associated with the current state with the smallest accumulated metric. Both wanted and interfering data sequences can be detected using this technique.

A metric generation element for the trellis of Figure 5 is implemented in Figure 2, where the boxes marked MAC indicate a multiply-accumulate operation, the output of which is sampled every data symbol period. The expression for the incremental metric has been taken, and simplified to group all terms not involving the received signal into one term

$$\alpha(a_0^{i,j}, a_1^{i,j}),$$

given in equation (4) below. This is then calculated each time the impulse response estimate is updated. A term involving the modulus of the received signal is removed (being independent of the data sequence

$$a_k^{i,j})$$

and the minimisation replaced by a maximisation.

$$\alpha(a_0^{i,j},a_1^{i,j}) = \sum_{l=0}^{\lambda-1} 2\mathrm{Re}[c_0(l,a_0^{i,j})c^*{}_1(l,a_1^{i,j})] - \left|c_0(l,a_0^{i,j})\right|^2 - \left|c_1(l,a_1^{i,j})\right|^2 \quad \ldots\text{ (4)}$$

The result is to make the metric generation process considerably more computationally efficient, providing the impulse response estimate does not require updating too regularly. For the single interfering signal only twice the number of multiplications are required over the conventional detector. However, the number of additions is increased in proportion to the increase in the number of states.

The super-state trellis approach, described above, provides an optimal solution to the detection of k + 1 signals in the presence of interference and Gaussian noise. The complexity of the super-state trellis means that its application is restricted to situations where the memory of the channel and modulation process is only a few symbols and when only a single interferer has to be suppressed. A simplification to the sequence estimator is now described, where only a subset of super-states are considered at each symbol interval.

A basic rule concerning the selection of this subset of super-states is that it should contain S states that differ in their state descriptor for the wanted signal. This is especially important at high signal to interference ratios, as otherwise performance will be sacrificed. The selection of the subset of states should be based upon straightforward comparison of transitions that merge in a common super-state, and supplemented by selection between super-states.

A procedure to select amongst super-states is illustrated in Figure 4. A selection is made amongst super-states that have the same state descriptor for the wanted signal, differing only in that for the interfering signals, the selection is made on the transition with the largest probability entering any of this set of super-states. This is denoted as wanted signal merger selection. Alternatively the selection can be made between states that merge in the state descriptor for the interfering signal. This type of selection may be preferable whenever the time dispersion in the channel for the interfering signal exceeds that for the wanted signal.

Using the wanted signal merger selection, a reduced state algorithm has been devised whereby (N + 1)-S states are retained. In each data symbol period the algorithm computes the probabilities for the transitions emanating from the (N + 1)S states retained from the previous symbol period. The algorithm then has to select (N + 1)S states from the M^{K+1}(N + 1)S expansions. There are S sets of M^{K+1}(N + 1) state expansions that merge in a common state descriptor for the wanted signal. From each set, the N + 1 state expansions with the largest probabilities, and which have a unique super-state are selected. State expansions which merge in a super-state have the conventional selection rule applied to them before the selection amongst merges in the wanted signal state. This ensures no duplication of super-states, but makes the number of operations for each subset selection dependent upon the super-states selected. Although this method of selection involves a sorting operation, a comparison with the M-algorithm shows that the complexity of this has been reduced by a factor of S. For a single interfering signal, and using 2S states in the super-state trellis, the complexity is 4.8 times that of the detector for a single signal. For a better understanding of the M-algorithm reference may be made to an article by J B Anderson and S Mohan, entitled "Sequential Decoding Algorithms: a Survey and Cost Analysis", IEEE Trans Volume COM-32, No 2, February 1984, pages 169 to 176.

Turning now to the channel impulse response estimator 7 as shown in Figure 1, its operation will now be considered in more detail.

The channel estimation technique herein described rely on some portion of the transmitted signal being known at the receiver. Typically this takes the form of some known data symbols inserted into the information content at the start of each transmission. The interfering signals are assumed to use different sets of data symbols in this known part. This practice is desirable whether the receivers in a mobile radio system use interference mitigation or not. Initially the problem of estimating the impulse response of both wanted and interfering signals where transmissions are arranged so that at the receiver the known data sequences are time-aligned. Clearly this is an impractical proposition, but it is a necessary step in the development of techniques which only assume knowledge of the wanted signal's known data content, allowing the condition of time-aligned transmissions at the receiver to be dropped.

For the case of a signal received in the presence of some additive noise, the most common method of estimating the channel impulse response is to find the set of coefficients ($\hat{h}$) which minimise the following quantity:

$$|\varepsilon|^2 = \min_{\hat{h}} \left\| \mathbf{r} - \hat{h}\mathbf{S} \right\|_2 \qquad \text{.... (5)}$$

A vector notation has been adopted in this section wherein, $\hat{h}$ is a $(D\lambda+1)$ element row vector, **S** a $(D\lambda+1)\mathrm{x}N$ circulant matrix, where N is the length of the known signal, **r** is an N-element row vector containing samples of the received signal at the position of the known data sequence and $\|.\|_2$ denotes the vector 2-norm. The coefficients obtained in the minimisation are those of a Wiener filter, and are the minimum mean square error estimate whenever the autocorrelation function of the transmitted signal is a delta function.

The extension of this procedure to deal with multiple signals is quite straightforward. The quantity involved in the minimisation to obtain the impulse response coefficients becomes:

$$|\varepsilon|^2 = \min_{\hat{h}_k} \left\| \mathbf{r} - \sum_{k=0}^{K} \hat{h}_k S_k \right\|_2 \qquad \text{.... (6)}$$

Differentiation with respect to the impulse response coefficients, and setting the result to zero yields a set of simultaneous equations, from which recursive and block estimation procedures can be derived.

$$\frac{\partial}{\partial \hat{h}_l}(\varepsilon\varepsilon^*) = -2S_l^H\left(\mathbf{r} - \sum_{k=0}^{K} \hat{h}_k S_k\right) \qquad \text{.... (7)}$$

Defining

$$\Phi_{i,j} = S_i S_j^H$$

as being the cross-correlation matrix between signals i and j, and $\psi_i = S_i r^H$, then the solution for the impulse response coefficients can be obtained by solving the following system of equations:

$$\begin{bmatrix} \Phi_{0,0} & \cdots & \Phi_{0,K} \\ \cdots & \Phi_{i,j} & \cdots \\ \Phi_{K,0} & \cdots & \Phi_{K,K} \end{bmatrix} \begin{bmatrix} \hat{h}_0 \\ \cdots \\ \hat{h}_K \end{bmatrix} = \begin{bmatrix} \psi_0 \\ \cdots \\ \psi_K \end{bmatrix} \qquad \text{.... (8)}$$

The above system of simultaneous equations can be solved by a variety of means. The block matrix formed from the correlation matrices $\Phi_{i,j}$, is Hermitian positive definite, and so Cholesky decomposition is an efficient and numerically stable way of obtaining a solution. In this connection attention is directed to a book by G H Golub and C F Van Loan, entitled "Matrix Computations", Johns Hopkins University Press, 1989.

Transmissions from different base stations within a cellular mobile radio system are unlikely to be synchronised, so the location of the known data sequences for the interfering signals will be offset from that of the wanted signal, and this offset may be such that they are non-overlapping. To find the location of each data sequence is a straightforward procedure. The received signal is fed into a buffer, and multiple correlators, each matched to one of the possible known data sequences are used to find the location of the known data sequences based upon finding the position with the maximum correlator output. This procedure can be applied to the wanted signal, but usually the location of the known data sequence for this signal will have been previously determined. At this stage using the magnitudes of the correlator outputs, the K largest interferers out of a possible N are selected. Given the location of the known data sequences for each of the K+1 signals, the process of estimating the impulse response of each signal is now performed, having regard to known sequence vectors.

Performing a cross-correlation operation with the known data sequences for the K largest interferers at the positions in the received signal obtained from the search operation above yields an estimate of the impulse response for the interfering signals. The same operation is used to obtain an estimate of the impulse response for the wanted signal. Denoting the j-th coefficient of the impulse response estimate for the k-th signal as $\hat{h}_k(j)$, then this initial estimate can be obtained from:

$$\hat{h}_k(j) = \sum_{i=0}^{N\lambda-1} r^*(i+q_k)S_k(i-j) \quad j \in [0,D\lambda] \qquad \text{.... (9)}$$

In the above equation r(i) are the samples of the received signal, $S_k(i)$ being the modulated samples of the known data sequence for the k-th signal, and q_k the location of the start of this sequence within the received signal. The known data sequence is of duration N symbols. At this stage, each impulse response will include components of all other impulse responses, due to cross-correlation effects between the modulated data sequences of the known signals, and those composing the received signal. For very large values of N, greater than 100, these terms will be sufficiently small to yield an adequate estimate of the impulse response of both wanted and interfering signals. However in most transmission formats for mobile radio applications the length of the known sequences will be considerably less than this, because such sequences have to be regularly transmitted, and so represent an overhead.

As a consequence, a technique is now described that allows the impulse response estimates obtained by the above correlation technique to be improved. From the K+1 estimates formed from the initial correlation, the one with the largest energy content is selected, and at the position of the known signal segment for this estimate, the data sequences of the remaining K signals are estimated using the impulse response estimates obtained from the cross-correlation in conjunction with the detection technique to be described later. The estimates of the data sequences will contain errors, but using decision reliability information obtained from the detector, the location of the P symbols most likely to have been in error can be identified, by finding the P smallest decision reliability values. These data symbols are treated as erasures, and so M^{KP} data sequence estimates result from the detection process (M being the number of data levels used). Data sequences for each of the K+1 signals are now known at one segment of the received signal. Equation (8) is then used to obtain estimates of the impulse response by computing the cross-correlation terms in the left and right hand side of equation (8) for each of the (M^{KP}/K) groups of data sequence estimates. The impulse response coefficients that when substituted into equation (6) along with the appropriate modulated data sequence minimise $|\epsilon|^2$, are the ones selected.

It will be appreciated that various modifications may be made to the arrangement just before described without departing from the scope of the invention and, for example, super state trellis selection may be utilised in the sequence estimator 10 in accordance with alternative techniques as will be apparent to those skilled in the art.

Claims

1. A communication system wherein known data sequences characterise both wanted transmitted signals and interfering co-channel transmitted signals, comprising a receiver for receiving a wanted transmitted

signal in the presence of unwanted co-channel interfering signals comprises signal sequence identifier means which includes a store for known data sequences and a correlator which serves to correlate received signals with the stored known data sequences, whereby the relative location in time of received signal sequences is identified, impulse response estimator means operative for estimating the impulse response of each signal the location of which has been identified, means responsive to the estimated impulse responses for producing in respect of each said response a set of possible signal configurations, and detector means including means for comparing the signals of each set with the received signal thereby to filter the wanted signal.

2. A system as claimed in Claim 1, wherein the sequence identifier means is fed with the received signal via a baseband signal converter and an A to D converter which in combination serve to provide digital signal samples of the received signal at baseband frequencies.

3. A system as claimed in Claim 1 or Claim 2, wherein the said means for comparing the signals of each set with the received signal comprises a metrics generator responsive to the said sets for providing signals for a sequence estimator comprising a trellis processor from which processor an output signal comprising a detected data sequence corresponding to the wanted signal is provided.

4. A system as claimed in any preceding claim, wherein the baseband signal converter is fed with a signal from a single antenna.

5. A land based cellular mobile radio system comprising apparatus as claimed in any preceding claim which is used to provide a demodulator/equaliser function, thereby to provide improved co-channel interference suppression.

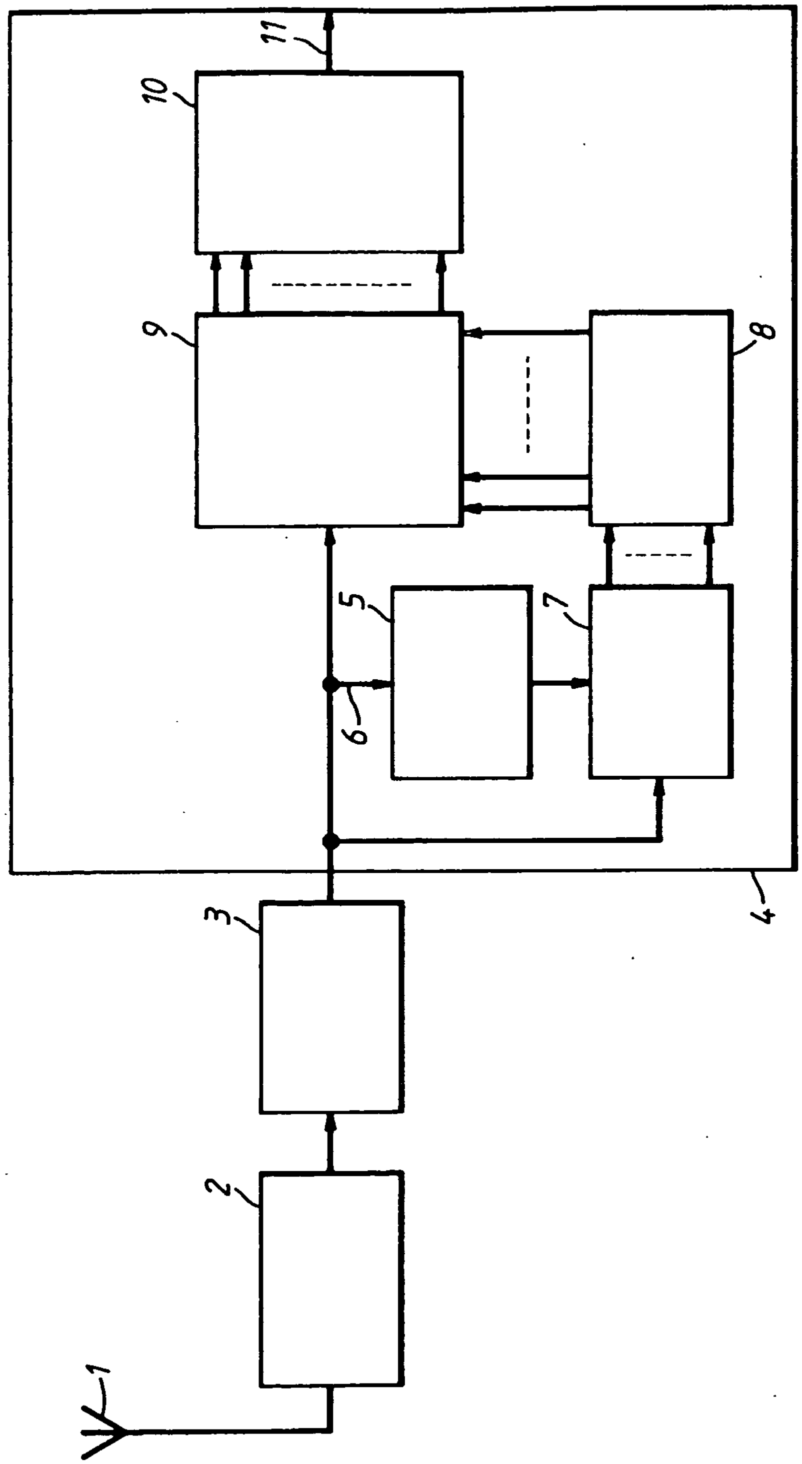

Fig.1

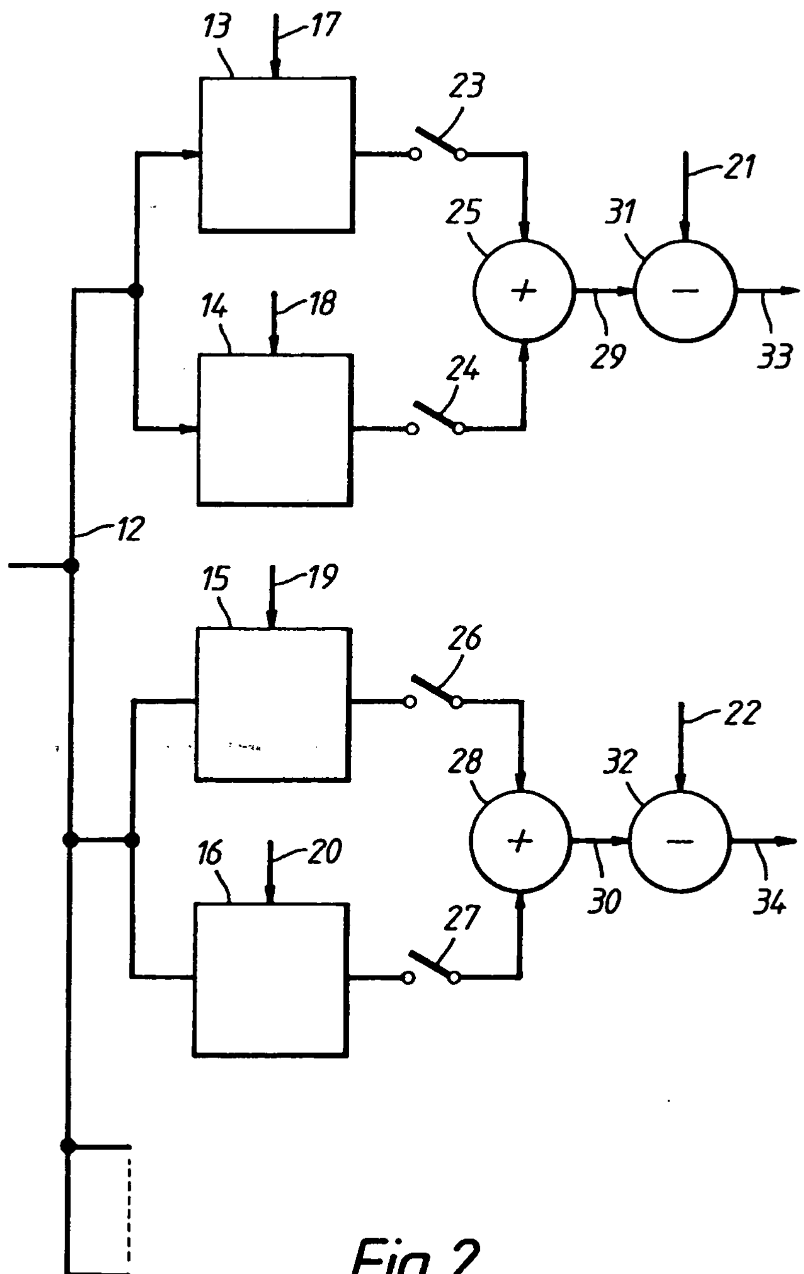

Fig.2

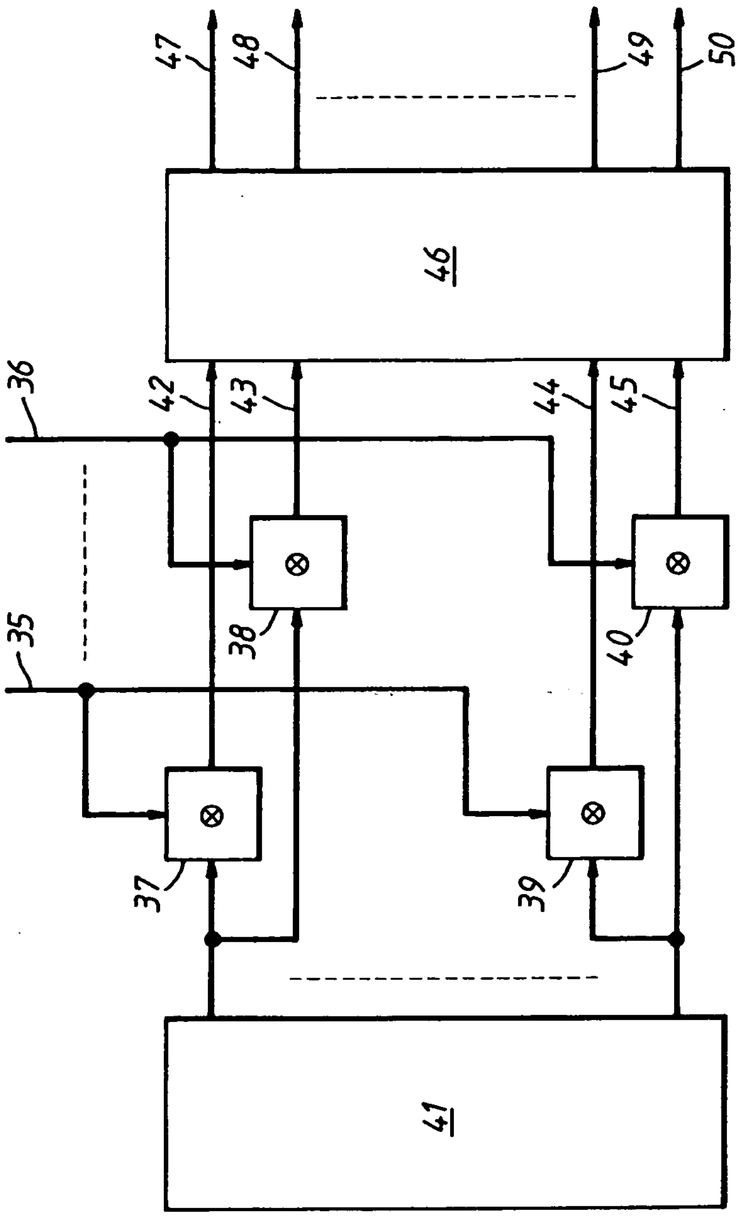

Fig.3

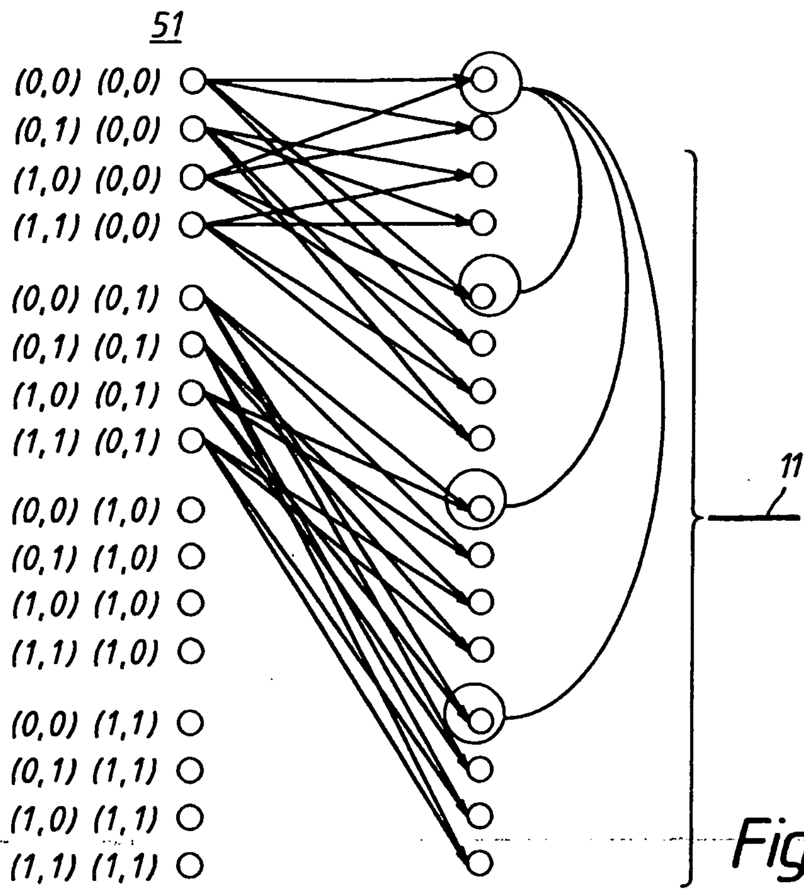
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Fig.4

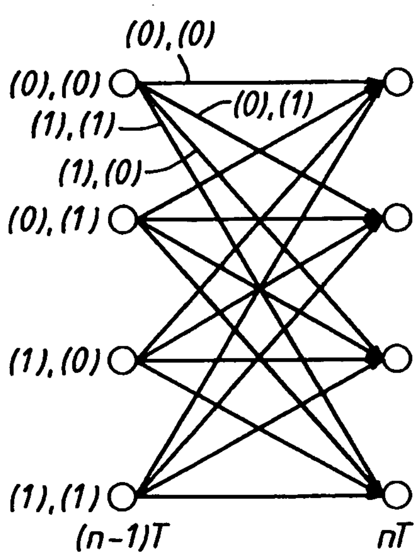
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Fig.5